Science of the Total Environment 954 (2024) 176735

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Designing nature to be a solution for climate change in cities: A meta-analysis

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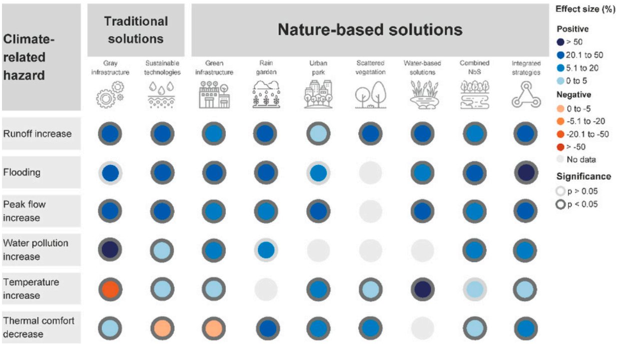
HIGHLIGHTS

- Nature-based solutions are key to promoting climate change adaptation.
- Incorporating NbS into plans doubles city resilience to multiple hazards.
- Efficient NbS strategy design considers hazards, management, and temporal scales.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jay Gan

Keywords:
Nature-based solutions
Climate change
Climate-related hazards
Ecosystem-based adaptation
Urban areas

ABSTRACT

Nature-based solutions (NbS) are designed as a win-win strategy to address societal challenges while providing biodiversity, social, and economic benefits. However, uncertainties and gaps persist, particularly regarding the criteria that define a NbS measure and the specific requirements for a solution to be fully recognized as such, which limit the full potential of these strategies in practice. Another persistent issue is the lack of data on strategy responses across different implementation scales (local, city, regional) and climatic zones (temperate, arid, tropical). This article provides an overview of the potential of NbS to promote climate adaptation in cities. Our meta-analysis, which compiled 7163 records from 89 articles worldwide, indicates that integrating NbS strategies with traditional approaches (gray infrastructure and sustainable technologies) is the most effective response to concurrently address multiple climate-related hazards. Flooding had the highest impact at 35.7 %, followed by increased runoff at 30.5 %. Peak flow and water pollution both had an impact of 10.3 %, while temperature

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Abbreviations: NbS, nature-based solutions; EbA, ecosystem-based adaptation.
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https://doi.org/10.1016/j.scitotenv.2024.176735
Received 25 July 2024; Received in revised form 26 September 2024; Accepted 2 October 2024

increase accounted for 5.7 %, and decreases in thermal comfort made up 5.0 %. We concluded that all evaluated strategies reduced the impact of climate-related hazards, but this reduction was twice as large when incorporating NbS (18.6 % *vs* 8.1 %). We also demonstrate that this effect is observed under projected climate scenarios, reinforcing the role of NbS in making cities more resilient and sustainable.

1. Introduction

Nature-based solutions (NbS)[1] were first proposed in 2008 (World Bank, 2008) and are defined as “actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively while providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016). By this definition, NbS must result in a net gain for biodiversity and ecosystem integrity but also be economically viable and based on inclusive, transparent, and empowering governance processes (Cohen-Shacham et al., 2016; IUCN, 2020; Pörtner et al., 2021). NbS can be understood as an umbrella term encompassing other widely used and already implemented concepts, such as ecosystem-based adaptation (EbA)[2] and ecosystem-based disaster risk reduction (Eco-DRR)[3] (IUCN, 2020), and include a range of ecosystems and green infrastructure-related strategies to tackle societal challenges, including the promotion of climate adaptation (Barber et al., 2020; Cohen-Shacham et al., 2016; Frantzeskaki, 2019).

Historically, the concepts within the NbS umbrella have primarily aimed at managing natural resources and improving ecosystem functions to reduce habitat loss and increase the provision of ecosystem services (Mace, 2014). In recent times, the emphasis has shifted to recognizing their role in combating the climate emergency by mitigating carbon emissions (Pan et al., 2023), lowering the risk of climate-induced disasters (Depietri and McPherson, 2017; Zhu et al., 2020), and counteracting biodiversity loss (Xie and Bulkeley, 2020). Currently, NbS are formally acknowledged for their potential to tackle a variety of societal challenges (IUCN, 2020; European Commission, 2021) beyond climate change mitigation and adaptation (McGreevy et al., 2022; Rao and Wilson, 2022) and the reversal of biodiversity loss (Seddon et al., 2020). In the current climate emergency, NbS are considered one of the best strategies to offer benefits, reduce vulnerability, and ensure the adaptation of socioecological systems (Díaz et al., 2018; Manes et al., 2022; Seddon et al., 2020). Especially in urban areas, practitioners have recognized NbS for their potential to address multiple challenges (Ferreira et al., 2020; Kremer et al., 2016; Miller and Montalto, 2019; Perotti and Stremke, 2018).

The transdisciplinary aspect of the NbS framework, bridging sectors such as biodiversity, health, and climate, places it as a powerful tool for enhancing approaches like the Nexus (Barber et al., 2020), which aims to advance climate adaptation agenda by leveraging synergies, managing trade-offs, and reconciling conflicting interests among sectors through an integrated approach (Global Water Partnership, 2019; Unai et al., 2022). This integration could amplify the transformative change – defined as “fundamental, system-wide reorganization across technological, economic and social factors, including paradigms, goals and values” (Butchart et al., 2019; Chan et al., 2019; IPCC, 2018; Mace et al., 2018; Sachs et al., 2019) of NbS (Palomo et al., 2021), a necessary step to achieve the Paris Agreement, the post-2020 biodiversity targets, and several of the Sustainable Development Goals (SDGs) (Chan et al., 2020; IPBES, 2019; IPCC, 2018).

However, uncertainties surrounding the role of the NbS continue to hinder its application, monitoring, and effectiveness in adapting to climate change while promoting social benefits (Martín et al., 2021; Pires et al., 2018; Xie et al., 2022). It remains unclear how effective different NbS strategies will be against the diverse climate-related hazards expected in the coming years (Martín et al., 2021; Seddon et al., 2020), especially given the projected increase in stormwater and temperature, which will affect all sectors of society (IPCC, 2022b). This highlights the critical need to synthesize existing data on NbS effectiveness compared to traditional approaches, including gray infrastructure and sustainable technologies. Furthermore, it is essential to understand whether this effectiveness evolves over time - from implementation to maintenance - under future climatic conditions. However, no study in the scientific literature integrates all available evidence to assess the potential and limitations of NbS across spatial and temporal scales, taking into account multiple implementation strategies and diverse climate-related hazards. In this study, we aim to provide insights to design optimal NbS strategies that consider both operational dynamics and resilience to climate-related hazards.

In this study, we aim to evaluate the performance of various NbS strategies in attenuating a range of climate-related hazards (*e.g.*, runoff increase, flooding, peak flow increase, water pollution increase, temperature increase, and thermal comfort decrease) compared to traditional strategies such as gray infrastructure and sustainable technologies, using a meta-analytical approach. Furthermore, we seek to evaluate how these dynamics operate across different management scales, from local to national, and under various climatic zones, considering current and projected climatic scenarios present in the scientific literature. We expect that the adaptation potential of different NbS strategies will be consistent, but the magnitude of such an effect will depend on the specific climate-related hazard addressed. Our results can guide the incorporation of NbS in the adaptation plans of cities worldwide by reinforcing identified potentials and addressing intrinsic limitations.

2. Material and methods

2.1. *Defining NbS as a strategy to face climate change*

We searched for terms related to the implementation of NbS in cities using the Web of Science database. The literature review was conducted using the following search terms: “ecosystem-based adaptation” OR “green infrastructure” OR “blue-infrastructure” AND “urban” OR “cit*” (to capture reference to cities). This search strategy yielded a total of 2697 articles. The term “Ecosystem-based adaptation” was chosen as a keyword for three main reasons: first, EbA and NbS are interconnected; second, EbA precedes NbS, which allows us to include a more extensive temporal perspective of studies on this topic; and third, EbA is exclusively linked to climate change, while NbS can be applied to a variety of societal challenges. Additionally, Web of Science was chosen for its comprehensive and representative coverage, given its substantial overlap with other major databases, such as Scopus (Gavel and Iselid, 2008).

The review compiled 7163 records from 89 articles assessing responses to various climate-related hazards after considering all selection criteria (Fig. 1). We analyzed articles focusing exclusively on adapting to

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[1] Nature-based solutions (NbS): actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively while providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016).

[2] Ecosystem-based adaptation (EbA): sustainable management, conservation and restoration of ecosystems, as part of an overall adaptation strategy that takes into account the multiple social, economic and cultural co-benefits for local communities (CBD, 2009).

[3] Ecosystem-based disaster risk reduction (Eco-DRR): The sustainable management, conservation and restoration of ecosystems to reduce disaster risk, with the aim to achieve sustainable and resilient development (Estrella and Saalismaa, 2013).

climate change in urban and peri-urban areas. Data extraction was performed directly from texts, tables, and graphs using DataThief III Software (Tummers, 2022). We excluded articles that (i) did not have available reference values or did not allow quantification in absolute values; (ii) used parameters based on maximum, minimum, or absolute values instead of average values (except when these were the only ones available); and (iii) included secondary parameters derived from variables already used (Table S1). We considered the natural deviation of all evaluated data, considering their specific value range, but performed preliminary analyses using the ROUT method to identify and remove definite outliers (Motulsky and Brown, 2006). No preliminary filters were applied to select specific climate-related hazards. We identified six categories: runoff increase, flooding, peak flow increase, water pollution increase, temperature increase, and thermal comfort decrease. A diverse range of metrics was encountered for each climate-related hazard, reflecting the varied perspectives proposed by different authors (Table S1). These hazards are expected to become more frequent in the coming years (IPCC, 2022a) and were chosen for being the most common in the literature.

2.2. *Defining NbS potential by using effect size measurements*

To evaluate NbS potential, we classified the multiple NbS strategies identified in the literature into five broader categories: (i) green infrastructure, which we consider to be the strategies using nature to enhance existing infrastructures such as green rooftops, walls, and facades; (ii) rain gardens, used to store water and promote water infiltration; (iii) urban parks, referring to medium to large green areas in cities; (iv)

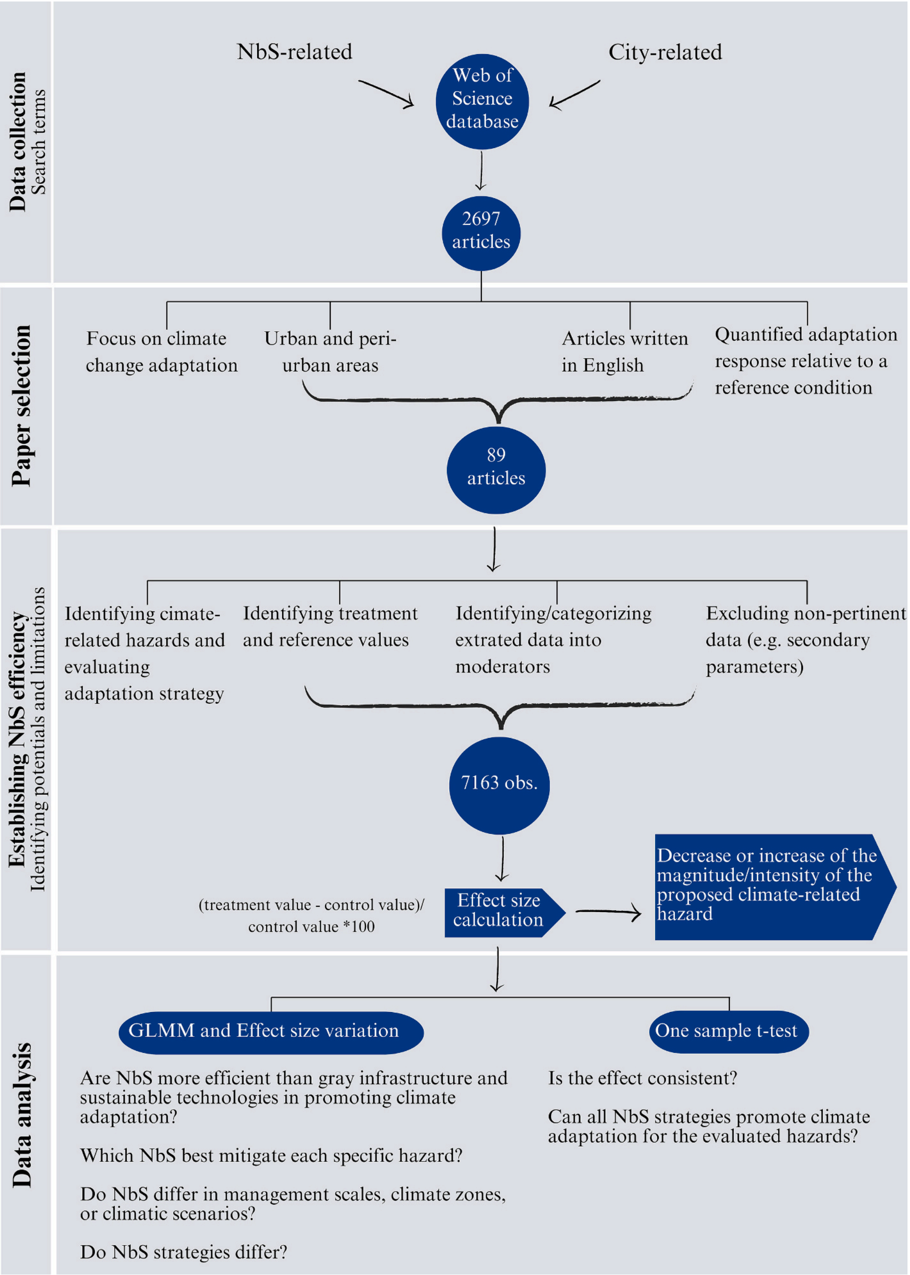

Fig. 1. Framework used for the development of the meta-analysis, detailing the four main subsequent steps of the process: (i) establishing comprehensive keywords for the literature search, along with the total number of articles identified; (ii) applying criteria and filters for the selection of relevant articles and extracting pertinent observations; (iii) formulating and interpreting the effect size, including the specific calculation formula; and (iv) adopting a protocol for conducting statistical analyses tailored to the research questions posed.

scattered vegetation, such as trees, shrubs, and grass; and (v) water-based solutions, related to the conservation and management of natural or artificial water bodies, such as lakes and ponds (Table 1). We also considered the integration of NbS with gray infrastructure (engineered artificial structures) or other sustainable technologies (*i.e.*, technologies that do not include nature in their conception but have a positive ecological impact, like porous pavements or reflective materials). Additionally, we evaluated gray infrastructure or sustainable technologies separately (Fig. 2, Table 1).

NbS potential was defined as the effect size, calculated as the percentage of the benefits obtained by implementing NbS compared to a reference condition, according to Eq. (1):

$$Effect\ size = (x - y)/y*100 \tag{1}$$

where x refers to the value observed when NbS is implemented and y to the value observed in a reference condition. The reference condition was established based on three potential landscape scenarios: (i) 100 % impermeable coverage, usually from modeling efforts evaluating water-related hazards; (ii) current landscape configurations with minimal NbS implementation; or (iii) current landscape configurations without any NbS strategies. These reference conditions were applied for all NbS strategies evaluated and can be found in Data S1. Positive effect size values indicate the reduction in the occurrence and/or magnitude of a given climate-related hazard; negative effect size values represent a compromise in the adaptation capacity of the environment promoted by a specific strategy.

Additionally, we assessed several factors that can influence the effectiveness of the adaptation strategies to identify the best way to design adaptation plans. These include the climate change predictions explored in the articles (current or projected climate scenarios); the management scales (local: *in situ* to neighborhood, city: municipality, regional: municipality to country); and the climatic zones (arid, temperate and tropical; Beck et al., 2018). This is relevant since benefits from NbS may be greater under milder current climates (Manes et al., 2022), while the adaptive capacity of natural systems may be exceeded under the ever-growing projected risks (IPCC, 2022a). Similarly, different adaptation strategies may respond better under varying management scales or in different climatic zones where baseline conditions vary. Here, we provide recommendations based on scientific evidence to design adaptation strategies using the most effective NbS for each context.

To test the differences among NbS strategies, we used Generalized Linear Mixed-effect Models (GLMMs) with the *nlme* package in R software (Pinheiros and Bates, 2000; R Core Team, 2020). We conducted individual models with NbS strategies, adaptation strategies classes (*e.g.*, NbS, gray infrastructure), management scales, climatic scenarios, and climatic zones as fixed factors. For all models, effect size was the response variable, and study identity was included as a random factor to account for bias caused by inherent differences among studies. To identify significant differences among strategies, we used *post hoc* comparison with the *emmeans* package in R software (Length, 2022), performing all pairwise comparisons using Tukey adjustment. Additionally, we performed one-sample *t*-tests using effect size values against a hypothetical mean value equal to zero to assess significant adaptation effects of NbS in the categories of each fixed factor, using GraphPad Prism software version 8.0.1 (GraphPad Software, San Diego, California, USA, www.graphpad.com, 2022). These analyses aimed to map variations in efficacy and identify where significant differences occurred. Further exploration of these differences can be found in Supplementary Material. To assess bias, we examined all models for bias using graphical

Table 1
Categories and definitions and number of records of adaptation strategies and climate-related hazards, implementation scales, climate zones, study types, and climate scenarios.

Group	Category	Definition	Example	Obs.	Articles
Adaptation strategies	Green infrastructure	Use of nature to create or improve infrastructure	Extensive green roof	998	25
	Rain garden	Establishment of small green areas with water storage	Bioretention cells	1977	14
	Scattered vegetation	Establishment of small-scale vegetation	Trees	644	32
	Water-based solutions	Promotion of water-related ecosystem conservation	Ponds	95	5
	Urban park	Creation of medium to big green areas	Allotment garden	205	13
	Combined NbS	Combination of nature-based solutions	Green roofs and trees	261	15
	Sustainable technology (traditional solution)	Ecologically beneficial technologies that do not include the presence and maintenance of nature itself	Permeable pavement	1582	22
	Gray infrastructure (traditional solution)	Engineered structures	Rain barrel	435	12
	Integrated strategies	Combination of NbS with sustainable technologies and/or gray infrastructure	Trees, rain garden, and cool pavements	914	26
Climate-related hazards	Flooding	Water overflowing onto land	Flood volume reduction	199	10
	Runoff increase	Increase in surface water flow	Runoff volume	3354	44
	Peak flow increase	Maximum flow rates	Peak discharge reduction	1763	16
	Water pollution increase	Water contamination increase	Combined sewer overflow	143	8
	Temperature increase	Changes in overall temperature	Land surface temperature	693	34
	Thermal comfort decrease	Discomfort perception due to environmental factors	Mean radiant temperature	1011	18
Implementation scale	Local	*In situ* to neighborhood	–	5311	67
	City	Municipality	–	1264	12
	Regional	Municipality to an entire country	–	588	12
Climate zone	Arid	Study areas within arid climates, including semi-arid (Bsh)	Brazil	985	6
	Temperate	Study areas within various temperate climates: Humid continental (Dfa, Dfb, Dwa); Humid subtropical (Cfa); Mediterranean (Csa, Csb); Oceanic (Cfb, Cwb)	Germany	5306	74
	Tropical	Study areas within tropical climates, such as tropical Savannah (Aw)	Ecuador	809	9
	NA	No climate zone defined	NA	63	4
Study type	Field data	Empirical data	–	719	14
	Modeling	Modeling effort	–	6444	75
Climate-change scenario	Current climate	Historical or current precipitation/temperature patterns	–	4975	82
	Projected climate	Climate projections integrating changes in precipitation/temperature patterns	RCP 8.5	2188	19

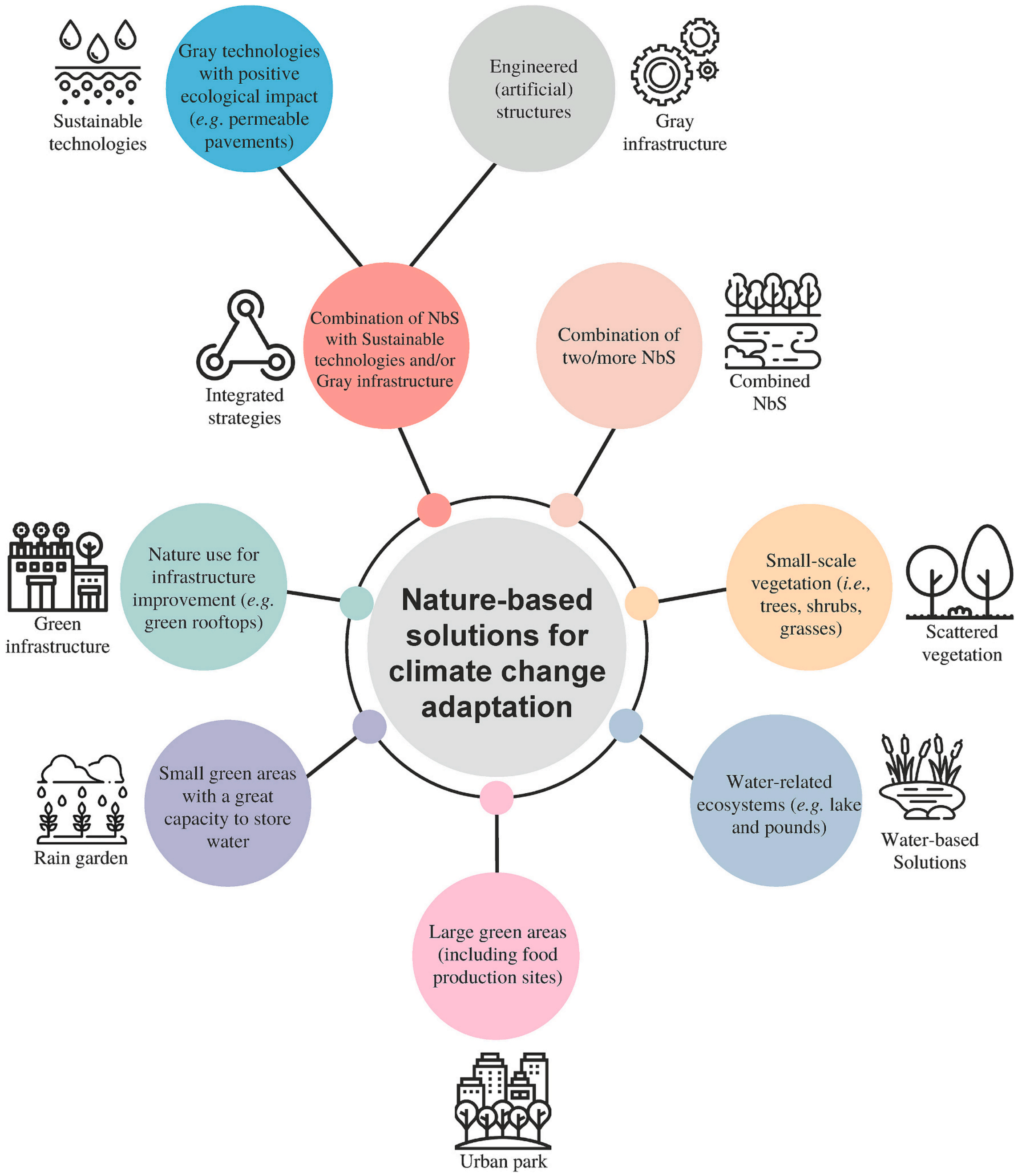

Fig. 2. Adaptation strategies focused on nature-based solutions (NbS) for climate change. NbS strategies are connected to the central gray circle, represented by icons with their definitions within the colored circles. The “integrated strategies” category combines elements of NbS and traditional strategies (*i.e.*, gray infrastructure and sustainable technologies) simultaneously, and thus, they are interconnected beyond the central circle.

funnel plots and evaluated the distribution of residuals through the qqplot function.

We highlight that in Supplementary Material – Data S1, parameters based on percentage increases or reductions were standardized to zero for comparison. Additionally, because climate-related risks are presented from various perspectives, including increases (runoff increase, temperature increase, and water pollution increase) and decreases (thermal comfort decrease), and considering variations in data presentation across articles, effect size signs were individually adjusted for result standardization. Finally, the reference conditions categories were applied for all NbS strategies evaluated.

3. Results and discussion

3.1. *NbS can attenuate multiple hazards, but its potential is context-dependent*

NbS effectively attenuated all climate-related hazards evaluated (Fig. 3, Tables S2, S3, and S4). NbS were most effective at flood attenuation, followed by decreasing runoff, improving water quality, reducing peak flow, reducing temperature, and increasing thermal comfort (Tables S2 and S4). Notably, all adaptation strategies significantly reduced water-related hazards (positive effect size), but gray infrastructure and urban parks did not present significant effects for flooding despite their positive mean effect size (Fig. 3, Table S2). We also observed the same potential for water pollution increase, except

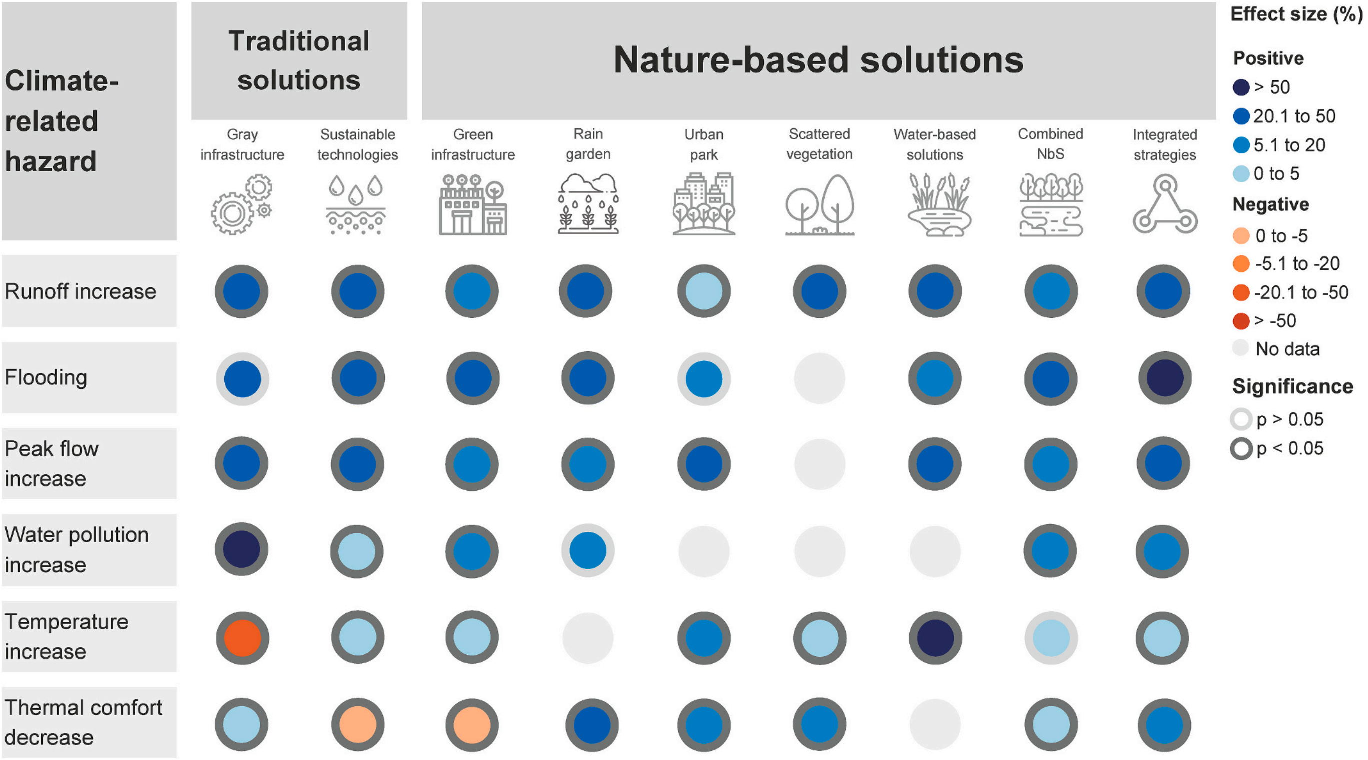

Fig. 3. Mean effect size (%) obtained for each adaptation strategy. Blue and orange inner circles represent the positive and negative impacts of the strategies, respectively. Darker colors represent stronger effects of each adaptation strategy. Significant impacts are presented considering a one-sample *t*-test (hypothetical mean equals zero) in the outer circles, where dark gray means significant effects while light gray non-significant effects ($p > .05$).

when considering rain garden effects (Fig. 3, Table S2). Lastly, temperature increase was ameliorated by all NbS and sustainable technologies strategies, but gray infrastructure significantly increased temperature (Fig. 3, Table S2). Thermal comfort was improved by all strategies except for green infrastructure and sustainable technologies, which worsened thermal comfort (Fig. 3, Table S2).

In terms of the magnitude of benefits, NbS were found to be twice as effective in attenuating climate-related hazards compared to gray infrastructure (18.6 % *vs.* 8.1 %), but sustainable technologies were the most effective (32.3 %) (Table S5; GLMM: $F_{2,6116} = 62.64$, $p < .0001$). However, sustainable technologies are designed to reduce some climate-related hazards (*e.g.*, runoff increase) and lack biodiversity elements, which can provide a range of co-benefits. In general, incorporating NbS into sustainable technologies and/or gray infrastructure maintained or increased their effectiveness in mitigating climate-related hazards (Table S5). Additionally, the potential negative impact of some sustainable technologies on thermal comfort highlights the need for integrating diverse NbS strategies to address multiple climate-related hazards effectively. Such pattern underscores the importance of combining these approaches to ensure that adaptation plans can simultaneously deal with multiple hazards (Fig. 3). Finally, we emphasize that no statistical bias was found in the model mentioned or in the subsequent analysis.

3.2. *Identifying potential and limitations to set up NbS across scale and water-related hazards*

NbS strategies addressing runoff increase, flooding, peak flow increase, and water pollution increase were the most common, comprising 76.2 % of the records ($n = 5549$). All NbS strategies were found to be able to promote adaptation to these hazards, despite some not being significant or not being evaluated in the literature review (Fig. 3, Table S2). These findings suggest that adaptation strategies can advance by integrating NbS strategies and replacing traditional infrastructure with more sustainable technologies, particularly in highly urbanized cities where implementing large NbS projects can be challenging. This is crucial to ensure that cities are well-equipped to promote adaptation in a timely to cope with the upcoming climate-related hazards.

NbS consistently attenuated the above climate-related hazards across multiple spatial scales, particularly locally (Fig. 4; Tables S3 and S6). At the local scale, the strategies reduce runoff, which in turn decreases flooding from exceeding storm drainage capacity and peak flows in downstream areas. In general, the benefits show a distance decay pattern related to the ability of watersheds and soil to handle water discharge (Hutchins, 2021). Therefore, considering the mechanisms by which NbS operate in promoting adaptation for flood events, they should be designed with a watershed perspective (Demuzere et al., 2014). It is also well known that green areas can contribute to water quality by reducing the total amount of suspended solids, nutrients, hydrocarbons, and heavy metals that reach water bodies (Davis et al., 2009). The decrease in peak flow and runoff also contributes to reducing total phosphorus and suspended solids (Odefey et al., 2012) and the probability of sewer overflow, which is strongly related to water pollution increase. Such positive effects of NbS on water quality can be combined with the direct effects on regulating water discharge to promote water security in a changing climate.

In fact, most of the records at the regional scale were focused on runoff increase, flooding, peak flow increase, and water pollution increase, primarily considering modeled scenarios at the watershed scale. These studies often explored multiple configurations of NbS strategies, including variations in type, distribution (*e.g.*, downstream, upstream), and dispersion (*e.g.*, aligned, clustered, random). For example, rain gardens and green roofs are inherently designed for expected local impacts, whereas forest restoration can present prominent responses at broader scales (CGEE, 2022). We suggest that the most appropriate scale for implementing NbS to adapt to these four climate-related hazards

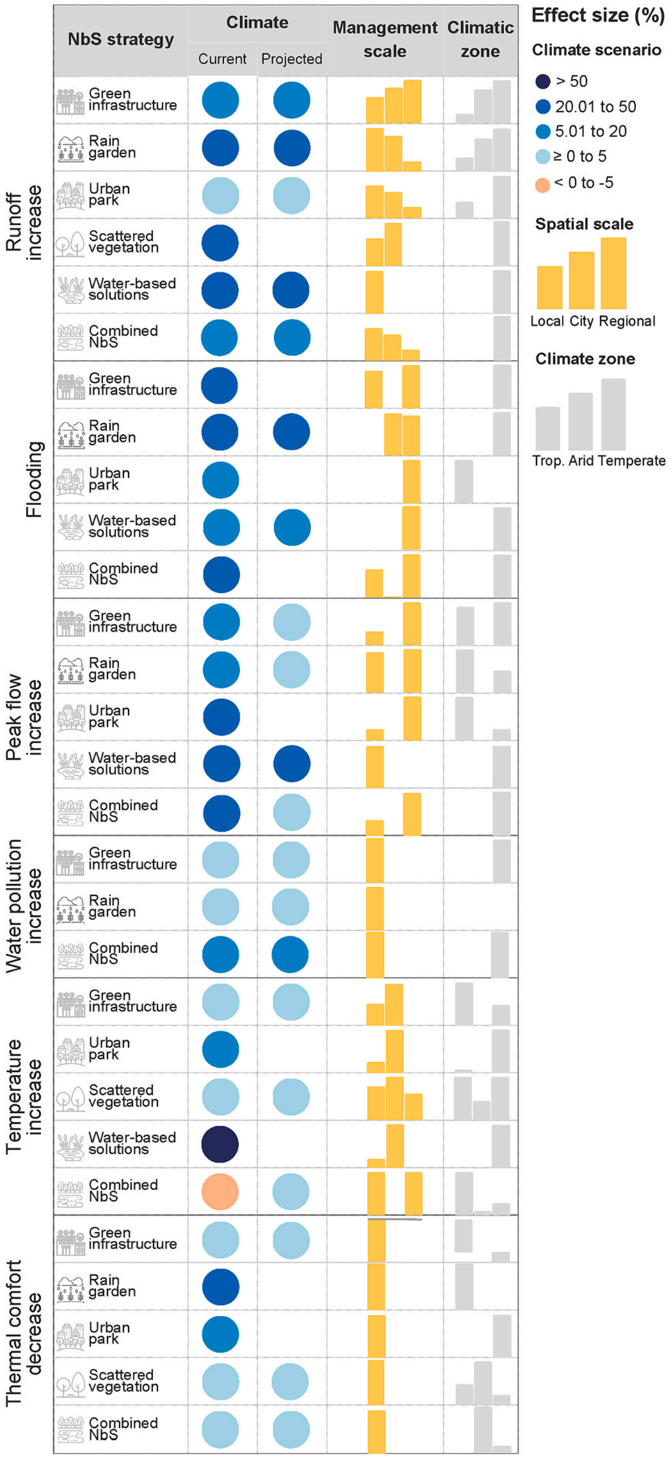

Fig. 4. Comparative potential of nature-based solutions (NbS) across various management scales (local, city, regional), climatic zones (tropical, arid, temperate), and climate change scenarios (current, projected) for different climate-related hazards. The colors of the circles denote effect sizes considering the climate change scenarios, reflecting varying levels of effectiveness. Blank columns indicate missing data. Note that comparisons across management scales and climatic zones are meant to reveal general patterns rather than specific values within each category. Consequently, the bars help compare the prevalence of different NbS strategies within each category, facilitating the analysis of how these strategies vary between categories and their relative importance.

depends on three main factors: i) the local viability of implementing each strategy, which can be related to its costs, maintenance, and available technology; ii) the specific climate-related hazard being addressed, which may respond differently to a particular strategy, and; iii) the methods used to evaluate the potential of the chosen strategy.

In this context, we conducted a GLMM test among observational and empirical data and found a significant difference between these variables (GLMM: $F_{2,70} = 28.56$, $p < .0001$). Regarding NbS strategies, the mean effect size was 8.3 % for field data and 19.6 % for modeling efforts. Evaluating the effectiveness of adaptation strategies is a complex task that involves considering a diverse array of quantitative and qualitative variables. Some of these variables pose challenges in measurement through monitoring or are characterized by high degrees of uncertainty (Kumar et al., 2021), particularly in the context of hydrological hazards. This complexity underscores why articles about hydrological hazards predominantly rely on modeling efforts.

Furthermore, the assessment of effectiveness is often hazard-oriented. In the case of drought, prominent numerical models identified in this review include MIKE-SHE and Storm Water Management Model (SWMM); for heat, Envi-met and Weather Research Forecast (WRF) stand out. These models come with unique assumptions, resulting in distinct advantages and disadvantages. Limitations encompass issues such as the propagation of input errors over time, high computational costs, substantial data requirements, and coarse spatial and temporal resolution (Kumar et al., 2021). Further research is needed to couple and integrate different spatial-scale process-based models into larger-scale models (Kumar et al., 2021). Additionally, we recognize the importance of addressing the integration of observational data into modeling efforts to validate such models, enhance modeling geometry, and improve local characterization and specification.

3.3. NbS for temperature-related hazards: tricky issues in designing strategies

Regarding adaptation strategies aimed at reducing temperature and increasing thermal comfort (9.7 % and 14.3 % of the records, respectively), most NbS were found to be related to the ability of green areas to provide cooling effects at local scales by providing shade, increasing evapotranspiration, and reducing heat island occurrence (Tiwari et al., 2021). The distance decay patterns identified for water-related hazards also influence the ability of NbS to adapt to temperature-related hazards, with benefits mainly realized in areas where NbS are implemented (Jia and Wang, 2021). Indeed, most records are related to *in situ* measurements through field data or modeling efforts to predict greener scenarios. These studies focused on providing detailed information about the best options to reduce temperature and potentially reduce energy consumption. It is well known that the energy sector is central to integrating biodiversity into climate-change adaptation strategies (Pörtner et al., 2021).

Few data (84) evaluated city-scale responses, mainly modeling surface/air temperature according to land use (Venter et al., 2020; Van Oorschot et al., 2021; Park et al., 2021; Fahmy et al., 2018). When calculating the mean effect size of the strategies based on their implementation scale, our results revealed that NbS implementation at the city scale has a more promising effect in reducing the temperature, being six times more effective than at the local scale (21.47 % *vs.* 3.43 %). This result reflects the inherent differences in temperature dynamics across these scales. Local-scale temperatures are influenced by specific land cover types and spatial variations, such as the presence of impervious surfaces and green spaces, which create significant microclimate differences. In contrast, city-scale temperatures are affected by factors that operate on a broader scale, such as urban heat island effects and overall city compactness (Buyantuyev and Wu, 2010; Cao et al., 2016; Cao et al., 2021). However, it is essential to highlight that interpreting percentual change for decrease can be tricky. A reduction of only 5 % in the mean effect size could already be significant and sufficient to promote thermal comfort. Nevertheless, the highest potential of integrating NbS into city-scale approaches indicates the potential impact of extensive green areas, including urban/peri-urban forests, green and cool roofs, and water-based solutions, such as swamps, lakes, and water bodies (Fig. 3; Table S2).

Also, it is important to highlight that the negative response of green infrastructure on thermal comfort (Fig. 3; Table S2) was mostly related to permeable pavements, green facades, and green roofs. Permeable pavements are not recommended for reducing the mean radiant temperature from a microclimatic perspective since they reflect more short-wave radiation than traditional pavements during the hottest hours of the day (Taleghani et al., 2016). Similarly, green roofs may not necessarily have a cooling effect on pedestrian-level microclimate due to their limited shading capacity, one of the most important functions for heat reduction. This limitation is exacerbated by their elevation above street level, which is the focal point for measuring thermal comfort-related metrics (Chen et al., 2009; Zölch et al., 2016). In general, strategies implemented on roofs or walls tend to be less effective than the ones at the street level, such as trees (Jia and Wang, 2021). However, it is important to consider the varying definitions of green infrastructure in the literature. Zölch et al. (2016), for instance, identified a similar pattern for green roofs while noting a positive effect for green facades. This diversity in effects underscores the necessity for careful evaluation of these strategies. Moreover, it is important to recognize that when analyzed in isolation, these strategies are categorized as “green infrastructure”. In contrast, when combined with other approaches or with other forms of green infrastructure (*i.e.*, green facades and green roofs), they are more appropriately assessed in this study under “Combined NbS” or “Integrated strategies”.

3.4. Exploring NbS potential across regions and time

Further studies should investigate the observed patterns across different regions and climates to ensure the consistency of these effects since there are great gaps in studies exploring the implementation of NbS. In particular, a vast majority of the records (74.4 %; $n = 5403$) were assessed within temperate climates, mainly in China, followed by arid (13.6 %; 985) and tropical (11.1 %; 809) climates, with a small number of records through modeling approaches without defined climatic regions (0.9 %). The limited number of records for arid and tropical climates restricts the comparison of NbS effectiveness among different climatic zones. Nonetheless, we observed a consistent and positive effect of NbS for all climate-related hazards worldwide, except for temperature increases in arid regions and flooding in the tropics (Fig. 4; Tables S3 and S7). This suggests that cities in arid and tropical areas may require more complex and tailored strategies to tackle climate-related risks. For instance, a broader range of NbS measures might need to be implemented, either in combination with or integrated into gray infrastructure and sustainable technologies, to enhance multifunctionality and create synergies between approaches. It underscores the need for further initiatives to assess the potential of NbS and various adaptation strategies in these regions, as highlighted by Manes et al. (2022).

Considering the potential of NbS to promote long-term adaptation, our findings indicate that their positive effects remained consistent even with a climate change perspective (GLMM: $F_{1,4108} = 51.86, p \leq 0.0001$). Around 32 % of records were based on future climate conditions, mainly considering business-as-usual scenarios. As we face a high degree of uncertainty in the climate change scenarios and trajectories projected for society's future, it is crucial to implement strategies that can effectively deal with environmental changes and safeguard human well-being. Evaluating the effects of NbS strategies within hazards, our results reinforce that the actual potential of NbS could be even greater in reducing future climate-related risks (Fig. 3; Tables S3 and S8; GLMM: $F_{5,4103} = 160.6228$, $p \leq 0.0001$). We demonstrate that the mean potential effect of NbS can be around 17 % higher in the future, considering climate changes, highlighting its importance in designing adaptation strategies in cities. It argues that the cost-effectiveness of these strategies should consider their increasing potential in the coming years (Table S9).

3.5. Define the climate-related hazard to design the solution

Considering the multiple ways to integrate NbS into adaptation strategies, we conclude that the choice of NbS strategy should be tailored to the target climate-related hazard. For example, rain gardens seem to be better suited for addressing flooding and integrated strategies to manage peak flow and runoff increase. This finding is primarily due to i) the extensive capacity of sustainable technologies to increase water infiltration by using technological materials, ii) the ability of gray infrastructures to store and rapidly drain water, and iii) the potential of natural surfaces to increase evaporation rates and water absorption. In contrast, water-based solutions seem the most effective way to address “temperature increase”. Water bodies are an essential element in urban ecosystems and are recognized for their ability to reduce temperature *via* evaporation during the hottest part of the day (Davis et al., 2009). Future NbS studies should explore the role of water bodies in promoting adaptation for non-water-related hazards since the limited number of records can potentially over/underestimate its role. Similarly, rain gardens had the highest potential to promote thermal comfort – a pattern that should be further evaluated (Tables S2 and S10).

In summary, mixed NbS strategies have a higher potential for adaptation to multiple climate-related hazards. Since each strategy contributes through different mechanisms, mixed strategies complement each other to realize the potential effectiveness of NbS and address multiple climate-related hazards. In this sense, temperature increase, thermal comfort decrease, and water pollution increase were more sensitive to the type of NbS implemented (Fig. 3; Table S2). As the effectiveness of NbS strategies for those hazards is more context-dependent, their implementation requires the design of more specific plans. This is especially important because implementing the same strategy can combine multiple effects for different climate-related hazards. Thus, we should consider the existing risks in each strategy. For example, despite the unmistakable effect of gray infrastructure to ensure water quality under climate change (Tables S2 and S10), it had a negative impact on temperature decrease (Fig. 3; Table S2). Additionally, the construction and operation of gray infrastructure contribute to increased greenhouse gas emissions (Thacker et al., 2019).

On the other hand, although tree and functional diversity can reduce water demand and increase the resilience of forest systems (Cardinale et al., 2011; Craven et al., 2016; Luan et al., 2024; Weiskopf et al., 2024), forest restoration - while promoting thermal comfort - requires substantial water availability during its early stages and may lead to water shortages in drier regions (Dib et al., 2023; Hoek van Dijke et al., 2022). Beyond their great potential to promote adaptation, mixed NbS strategies offer an insurance effect, reducing potential trade-offs among responses to multiple climate-related hazards. Furthermore, given that simulated values represent approximately 90 % of the available data and show a mean effect size 57 % higher than observed values, this may indicate that the models do not capture additional factors influencing NbS potential. These factors could include governance dynamics, political contexts, and other elements typically overlooked in modeling studies. Therefore, observational studies are crucial for validating and complementing simulation results, ensuring that the full potential of NbS is realized in practice.

4. Conclusion

NbS as a strategy for climate adaptation has gained attention in most multilateral environmental agreements in recent years and should be implemented worldwide in the coming ones. Beyond evaluating its adaptation potential worldwide, we advocate for fundamental improvements in the definition and role of NbS to enhance its implementation. Furthermore, advancing research on the potential of each strategy to address multiple climate-related hazards is crucial for designing effective adaptation plans. We demonstrated that, despite differences among strategies, NbS consistently promote climate adaptation more effectively or equivalently than traditional strategies across scales, climatic zones, and implementation conditions. Future studies should focus on reducing current research gaps, especially in tropical and arid zones.

As most megadiverse and developing countries are located in these regions, they have a unique opportunity to leverage their natural resources to promote climate adaptation while ensuring biodiversity conservation, health, food, and water security, thereby advancing a nexus approach agenda (Pires et al., 2021). Aligned with the UN 2030 Agenda, the post-2020 biodiversity framework, and current climate agreements, the integration of NbS plays a crucial role in making cities and human settlements more inclusive, safe, resilient, and sustainable. Beyond climate adaptation, NbS are expected to enhance urban ecosystem services and biodiversity, fostering more equitable and livable spaces for both humans and other species. These co-benefits are vital for increasing urban system resilience and advancing social and environmental equity (IUCN, 2020). By improving well-being and fostering community cohesion, NbS present a significant opportunity. It is essential to involve society in restoration and other nature-based solutions efforts, reconnecting people with nature, raising awareness of societal benefits, and generating public demand for healthier natural environments.

We demonstrated that all NbS strategies can be designed to buffer one or multiple climate-related hazards, and a one-size-fits-all approach to climate adaptation is not viable. However, optimizing implementation efforts is both possible and necessary, especially considering costs and the growing need to enhance multifunctionality at all spatial levels. This optimization fosters synergies across multiple benefits (Paulin, 2020). The outcomes from this study highlight the importance of integrating NbS strategies to promote climate adaptation, given their strong interconnections and wide-ranging co-benefits. We conclude that utilizing mixed NbS strategies, along with sustainable technologies and gray infrastructures, offers the most comprehensive approach to tackling climate-related hazards while simultaneously enhancing urban biodiversity and livability.

CRediT authorship contribution statement

Helena A. Prado: Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tauany Rodrigues:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation. **Stella Manes:** Writing – review & editing, Data curation. **Thais Kasecker:** Writing – review & editing, Conceptualization. **Mariana M. Vale:** Writing – review & editing, Supervision. **Fabio Rubio Scarano:** Writing – review & editing, Supervision. **Aliny P.F. Pires:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no competing interests.

Data availability

All data required to evaluate the conclusions presented in the paper are fully accessible within the paper and supplementary materials. For access to the complete dataset, please visit https://github.com/HelenaAlvesPrado/Meta-analysis_NbS.

Acknowledgment

This project was funded by the “Conselho Nacional de Desenvolvimento Científico e Tecnológico” (CNPq) - Process 423057/2021-9; and “Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ)” - Rio de Janeiro, Brazil (Process E-26/010.001939/2019; Process E-26/211.988/2021; Process E-26/201.454/2022; Process E-26/210.070/2024). Helena A. Prado was funded by the grant #88887.629784/2021-00 (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - CAPES).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.176735.

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